Project	AtlantOS – 633211
Deliverable number	D4.3
Deliverable title	Synoptic multi-variable multi-glider study
Description	Analysis and report of sustained multi-glider deployments, providing detailed methodology of the deployment strategy, piloting, and calibration process. The analysis will deliver methods for the synoptic interpretation of all ocean variables over multiple timescales.
Work Package number	WP4
Work Package title	Interfaces with coastal ocean observing systems
Lead beneficiary	NERC
Lead authors	Matthew Palmer
Contributors	Charlotte Williams, Kevin Horsburgh
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Comments	

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Last updated: 03 July 2018

Stakeholder engagement relating to this task*

WHO are your most important stakeholders?	☐ Private company If yes, is it an SME ☐ or a large company ☐? ☐ National governmental body ☐ International organization ☐ NGO **X others** Please give the name(s) of the stakeholder(s): Marine and environmental research community Statutory marine monitoring agencies Marine robotics industry
WHERE is/are the company(ies) or organization(s) from?	**X Your own country** ☐ Another country in the EU ☐ Another country outside the EU Please name the country(ies): Research : Global Monitoring: National Industrial: Predominantly USA
Is this deliverable a success story? If yes, why? **If not, why?**	**X Yes**, because this case study provides a unique and highly valuable time series for use by the marine science community and provided a test case for emerging technologies. ☐ No, because …..
Will this deliverable be used? **If yes, who will use it?** **If not, why will it not be used?**	**X Yes**, by the marine science community for research into physical and biogeochemical functioning of shelf seas and for validation of regional scale ocean models. Lessons learned are already being adopted into new observational programmes. ☐ No, because …..

NOTE: This information is being collected for the following purposes:
1. To make a list of all companies/organizations with which AtlantOS partners have had contact. This is important to demonstrate the extent of industry and public-sector collaboration in the obs community. Please note that we will only publish one aggregated list of companies and not mention specific partnerships.
2. To better report success stories from the AtlantOS community on how observing delivers concrete value to society.

*For ideas about relations with stakeholders you are invited to consult D10.5 Best Practices in Stakeholder Engagement, Data Dissemination and Exploitation.

Title: **Synoptic multi-variable multi-glider study**

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Executive summary

This report provides a detailed overview of a series of coordinated glider deployments made in the Celtic Sea that were used to address the objectives of AtlantOS WP4 task 4.2. This long-term, multiple vehicle deployment tests the capability of ocean gliders to provide a synoptic study of physical and biogeochemical functioning in a temperate shelf sea, with the longer-term aim of providing a framework for operational coastal oceanography that is globally transferable. The AtlantOS WP4 work extended and complemented an existing project (funded by NERC in the UK). The analysis, carried out under AtlantOS, enabled the broader recommendations for multi-variable glider deployments that are reported here and which was our WP4 objective. In total, 22 autonomous ocean gliders were deployed over a 17-month period. This case study focuses on the on-shelf component of this study, which includes a repeat 120km long transect between the Atlantic shelf break and the inner shelf and a series of short term deployments of specialist gliders that provide additional parameters at fixed station locations. The experiment was highly successful, providing an extensive, high-resolution, multivariable dataset that captures the key components of the seasonal cycle of stratification and associated biogeochemical responses.

This report presents useful information on planning strategy, navigation and quality control associated with this long-term series of glider deployments and presents data and analysis of collected data. Finally, recommendations are provided for future studies of this type. These are summarised below.

Recommendation 1: Glider users should keep an open dialogue with platform and sensor manufacturers to ensure optimal configuration of platforms based on user requirements. Recognised data quality standards should be adopted to ensure good data quality and unified data formatting for global transferability.

Recommendation 2: To maximise data collection capability it is recommended to provide secondary gliders in close proximity to primary units. The second biggest risk of data loss is from biofouling during summer months. Duplication of sensors on single gliders is unlikely to resolve this issue, so efforts should be made to employ best practice techniques to prevent biofouling following advice provided under AtlantOS WP6 task 6.4. Sensor duplication would be beneficial to check for sensor drift, however provision of a secondary glider in close proximity would enable regular cross-calibration and opportunities to identify sensor drift; that is the recommended best practice.

Recommendation 3: Glider pilots and managers should aim to incorporate all available technologies and predictive capability to optimise navigation, particularly in highly dynamic environments such as continental shelf seas.

1. Introduction

AtlantOS Workpackage 4 '**interfaces with coastal ocean observing systems'** aims to boost the development of new products and services in coastal operational oceanography through the transfer of skills and knowledge into less well developed coastal systems. Task 4.2 of this workpackage uses multiple deployments of ocean gliders to test the capability of marine autonomous vehicles to synoptically assess physical and biogeochemical functioning in shelf sea systems. The task, which forms the basis of this report, will illustrate cross-calibration approaches between autonomous platforms and other ocean platforms (such as ships and moorings) and will pave the way for the improved operational use of ocean gliders in shallow seas globally.

Ocean gliders are rapidly becoming standard inclusions to oceanographic research operations and significant investment is being made into enabling open accessibility to multiple glider platforms that offer a large range of sensors and data delivery capabilities. There is particular emphasis on the availability and effectiveness of biogeochemical measuring systems which will be required in fulfilment of many coastal monitoring ambitions over the next decade (particularly in light of the IOC Decade of Ocean Science for Sustainable Development and attaining UN SDG14). The introduction of new platforms to any area of environmental science or monitoring however, requires careful consideration of how existing data quality assurance and control implementations developed for different platforms must be suitably modified to ensure acceptable levels of data return. Also, the introduction of new platforms for ocean observing introduces new pressures on already established networks and facilities, such as those handling the management, deployment and recovery of ocean instrumentation; data centres; manufacturers; and downstream customers or stakeholders.

The last decade has seen each of these considerations tested by the rapid acceleration in use of ocean gliders as marine research platforms. This acceleration has been partly attributable to technological advances from satellite communications and reductions in associated costs, increased battery performance and increased confidence in low-power sensors. An often-cited incentive for investment in glider technology however, has been the potential for reducing costs associated with expensive ship-based operations, either through a direct replacement for data collection or through increased efficiencies that gliders may provide when operating alongside ships and other traditional ocean platforms.

The UK has taken a leading role in the use of providing ocean gliders to the marine science community through the Marine Autonomous and Robotic Systems (MARS) facility, based at the UK National Oceanography Centre in Southampton. This national facility provides open access for scientists and technologists from the UK and eligible international partners to access a fleet of over 30 ocean gliders and provides the technical support, data delivery and data management services that users may require. The availability of large fleets of gliders such as those provided by MARS has prompted funding opportunities to test whether these platforms can provide long-term, sustained, multi-variable studies of large ocean areas that might enable synoptic monitoring capability.

In this report, we present a case study in the Celtic Sea that tests the endurance, cost-effectiveness, data quality and repeatability of ocean gliders over large areas (order 100km) within UK shelf sea waters. This case study uses data collected under the NERC-DEFRA funded Shelf Seas

Biogeochemistry programme during March 2014 to August 2015, the aim of which was to improve understanding of physical, biogeochemical and ecosystem functioning throughout seasonal shelf sea cycles. The full analysis of this dataset and recommendations drawn was made possible under the AtlantOS project.

2. Celtic Sea case study

The UK Shelf Sea Biogeochemistry programme (SSB, www.uk-ssb.org) aimed to strengthen understanding of the cycling of nutrients and carbon and the controls on primary and secondary production in UK and European shelf seas, in order to increase understanding of these processes and their role in wider biogeochemical cycles over a range of scales. Initial glider aspirations were limited to only 3-4 deployments, concentrated mainly on the shelf break region of the Celtic Sea for a few months in 2014 and a single deployment over the 2014-2015 winter period linking the shelf break to inner Celtic Sea (see map in Figure 1 for reference). AtlantOS WP4 provided additional funding that helped expand the aspirations of the programme from this otherwise *light touch* glider campaign to what became a sustained series of deployments including 22 ocean gliders carrying a range of sensor packages covering physical and biogeochemical parameters and delivering multi-variable time series from March 2014 to August 2015. This was achieved through the direct provision of additional researcher time under AtlantOS, combined with the growing confidence in marine autonomy in the oceanographic community that led to significant investment in UK marine autonomy infrastructure.

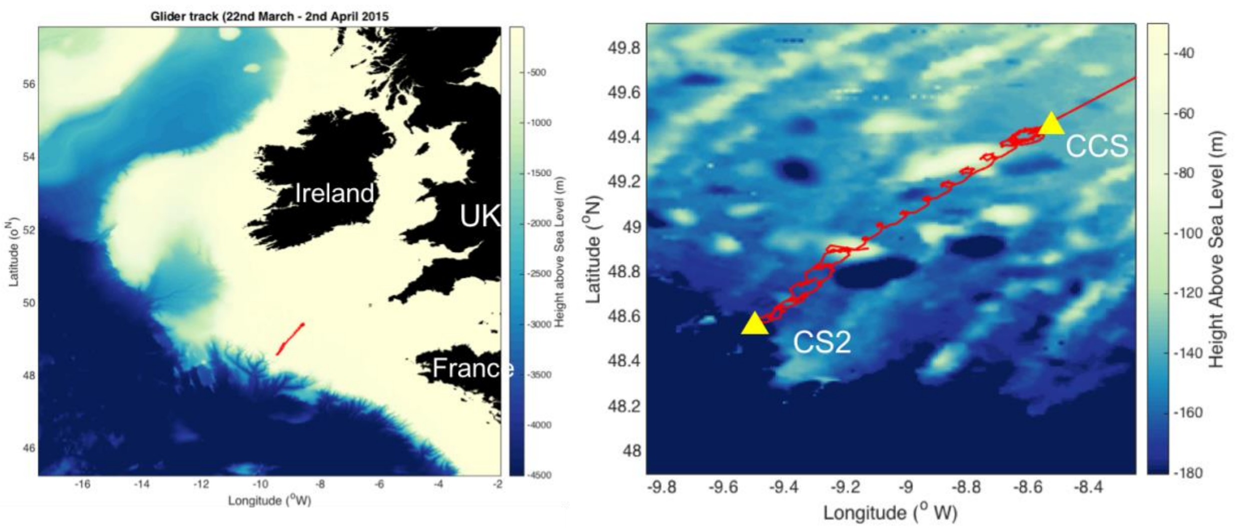

Figure 1: Multiple glider transects were made between stations CCS and CS2 (right, yellow triangles). The considerable influence of tidal currents is evident by the helical nature of the glider track (red line). CS2 was located at the 200m isobath, which indicated the transition between shallow shelf seas and the steep shelf slope region connecting the Celtic Sea to the Atlantic Ocean. CCS was located 120km on-shelf from CS2 in a depth of 140m.

2.1. Strategy

While initial plans were focused on shelf break and off-shelf deployments to identify across shelf exchange and off-shelf transport, a change in strategy was implemented during 2014. This was driven partly by additional resources arriving during the operational stages of the experiment, which included additional researcher funding from AtlantOS WP4 that provided capacity for increased effort on glider missions. A new series of sustained glider deployments was planned, linking shelf break station CS2 and inner shelf station CCS with supporting deployments of specially equipped gliders at CCS and CS2. The aim of the transect was to provide high spatial and temporal resolution data resolving mesoscale to sub-mesoscale physical and biogeochemical processes and the modification of such processes through the winter-spring-summer transition of the seasonal cycle. This new mission was driven in part, to help meet the objectives of AtlantOS task 4.2, which was well aligned with the scientific objectives of the SSB programme.

All gliders were deployed and recovered from the RRS Discovery; a state-of-the-art oceanographic research vessel owned by the UK Natural Environment Research Council (NERC) and operated by the National Oceanography Centre (NOC). Full ship specification can be found on the NOC website (www.noc.ac.uk/facilities/ships/rrs-discovery). Our programme was amongst the first operational programmes supported by this new vessel. Technical limitations of the new ship meant that small boats were not able to be used for deployment or recovery of gliders, as would have been the preferred option to minimise the risk of damage to the gliders. Instead glider operations were managed using deck cranes over the side of the ship (Figure 2).

Figure 2: Left, the Seaglider, with integrated micro-fluidic nutrient sensor is relatively easily deployed from RRS Discovery during SSB 2015 in calm seas. Middle, an ocean microstructure glider (OMG) requires more cautious deployment so is held horizontally during deployment. Right, the OMG recovery is however, simplified due to the detachable nose cone that provides a lifting point for the ship's crew.

Two types of glider were used in this study, Seagliders (Eriksen et al, 2001) and Slocum Coastal gliders (Jones et al, 2005). The Slocum gliders undertook all of the transect operations as their configuration is best suited to shallow water operations (less than 200m). In their Coastal configuration (as was used here) the Slocum uses a solid piston to alter its buoyancy, which is much quicker method than the deep water method employed by the Seaglider and deep water variants of the Slocum glider. This capability makes the Slocum Coastal glider the most efficient option for shallow water operations by maximising glider time between inflections and increasing depth averaged horizontal speed. Please refer to the cited papers and others for technical explanation of glider propulsion. The following sensor configurations were used for 'standard' gliders (both Slocum and Seaglider) and represent typical manufacturer provided scientific payloads,

1. Seabird glider payload CTD: measuring conductivity, temperature and depth (pressure) for the additional derivation of salinity and density.

2. Wetlabs ECO puck: provides single-wavelength measurement of chlorophyll a and coloured dissolved organic matter (CDOM) fluorescence and optical backscatter (OBS).

3. Aanderra oxygen optode: to measure absolute oxygen concentration in seawater and oxygen saturation electrochemically.

Additional sensors were included to the following specialist gliders.

4. Ocean Microstructure Glider (OMG): A standard Slocum coastal glider with a Rockland microstructure sensor payload externally fitted (see middle and right images in Figure 2). This sensor provides very fast sampling (512Hz) shear and temperature capability, from which turbulent parameters can be derived that enable estimates of ocean mixing. Refer to Palmer et al (2015) for technical details.

5. Nutrient Sensor Enabled Glider (NSEG): A standard Seaglider with upgraded internal space available in the rear of the vehicle to permit installation of a 'Lab-on-a-Chip' microfluidic spectrophotometric sensor, developed at the NOC. The deployments of these sensors provided the first successful use of the nitrate+nitrite version of these sensors on ocean gliders. Full technical details and presentation of results can be found in Vincent et al (2018).

The primary objective of the repeat glider transect was to resolve meso- to sub-mesoscale variability in physical and biogeochemical parameters throughout winter to summer transition of the seasonal cycle of stratification, which is typical of temperate latitude continental shelf systems. To achieve this with the available resources, single glider deployments were planned with deployment and recovery designed to take advantage of RRS Discovery operations. Much of these operations were focused on servicing of moorings at the CCS station and so deployments were managed from this location. This provided suitable opportunity for in situ calibration using nearby moored sensors and ship based CTD measurements and water samples. In total, 5 gliders were used to collect data over a 9-month period (refer to table in Appendix A, deployments shaded blue). The deployment of 2 gliders during Q2 2015 was in response to failure of glider Fortyniner soon after deployment and subsequent replacement with glider Nelson.

In addition to the repeat glider transect, the specialist gliders OMG (OMG2 and OMG3) and NSEG (Denebola) were deployed simultaneously for relatively short periods of 1-3 weeks at either station CCS (OMG and NSEG) or at the shelf break station CS2 (OMG only). Limited endurance due to increased power demands on these gliders meant that deployments of several months was not considered possible. The nature of processes under investigation with these specialist gliders, which was primarily the vertical flux of nutrients across the seasonal thermocline, was considered too complicated to resolve over large areas. These gliders were therefore managed in a 'virtual mooring' mode, holding station close to the fixed locations of CCS and CS2. For deployment periods refer to appendix A, deployments shaded purple and yellow.

2.2. Piloting, navigation and communication.

Each glider deployed during the programme was managed by the MARS facility at NOC Southampton. This management included remote piloting of each glider. While the on-shelf operations of this case study involved only small numbers of gliders there were additional glider deployments at the shelf break, slope regions and some coastal stations (see appendix A for details). This meant that up to 7 gliders were deployed at one time, requiring a shift pattern being adopted monitoring glider activity and performance. Each glider is able to follow its designated list of waypoints and every effort was made to avoid amendments to waypoint schedules, which minimised the amount of contact time pilots were required to directly communicate with individual gliders and so the missions were largely manageable by a single pilot. The exception to this was during deployment and recovery periods when command and control is required to coordinate profiling and surfacing with the ship's crew and CTD calibration schedule. Direct satellite links to NOC dock servers were used to enable suitably trained personnel on board to manage gliders alongside technical personnel responsible for handling the gliders in or out of the water. When connections or insufficient suitably trained personnel were available on board, glider communication and navigation was managed from shore and direct communication with technical staff managed by satellite telephone.

To enable the gliders to continue uninterrupted operation in shallow shelf sea waters for 3-month periods requires optimal flight preparation for efficient power consumption. This is achieved through ballasting the gliders as close to neutral buoyancy as possible so that the minimum amount of energy is expended to achieve optimal flight. Optimal flight is typically aimed at gliders achieving maximum distance covered under minimum power consumption, however consideration must be made to the horizontal resolution required to resolve features of interest. In the shelf seas, important length scales to resolve are typically of the order of physical topographic features that drive much of the observed variability. The banks and ridges that make up the Celtic Sea floor are typically of the order 10s of kilometres in length. Additional features of interest are tidal mixing fronts that may form around shallow topography. Suitable resolution of the thermal gradients that make up these fronts can be achieved within approximately 1km resolution. The typical glide angle (25° from horizontal) and vertical velocity (approximately 15cm/s) result in a single up or down profile a distance approximately twice the profile depth. A typical 100m deep profile would produce a vertical multi-variable profile approximately every 200m. This high resolution means that for the transect part of this study, gliders were optimised for maximum efficiency as horizontal length scales were much larger than that resolved by the glider.

For the specialist glider operations with the OMG however, the glide angle was an important consideration as the high-resolution measurements of the microstructure sensors are highly susceptible to mechanical noise if the glider produces excessive eddy shedding or becomes unstable during flight through dynamic features, such as internal waves or turbulent eddies. OMG flight was therefore optimised to be as close to vertical as possible. The upper limit for this specialist glider was only slightly higher than standard operation and was typically 30° from horizontal. Since this glider was deployed as a virtual mooring however, maximising distance travelled was not a consideration and so this did not compromise the mission.
For the nutrient glider NSEG, a different flight configuration was required. While the standard suite of instruments on the gliders collect samples electronically and therefore near instantaneously, the time required to collect a single nutrient sample is several minutes, typically 10 minutes duration. This is equivalent to the time taken for a single 100m profile. To ensure a stable sample collection with this sensor the NSEG operated in *loiter* mode during data collection, maintaining a near constant depth. For a full summary of operations with the NSEG refer to Vincent et al (2018) with additional detail in section 3.4.2.2 of this report.

2.3. Quality control

Providing good quality assurance and control from data collected from marine autonomous vehicles presents a challenge to the marine science community. Marine autonomous vehicles such as gliders are designed to be low power for long endurance. While the sensors used on such platforms are comparable in quality and capability to those used on state-of-the-art research vessels, the opportunities to cross-calibrate sensors with discretely analysed water samples or with other comparable sensors is often limited. In the Celtic Sea case study glider missions were planned for up to 12 weeks duration, with ship-based calibration of sensors only available during deployment and prior to recovery. Ship time was severely limited during this multidisciplinary research programme and so CTD operations used for glider calibration purposes were typically combined with ongoing research objectives and so may not always have been optimised for this purpose. In addition, safety considerations often put gliders many kilometres away from the ship during CTD operations. This introduces likely disparity between measurements as separation of 5-10km, which was typical during these operations, was of the same order as important physical and biogeochemical length scales and potentially in excess of tidal excursion and so local horizontal gradients could invalidate samples for calibration. Similar concerns about safety prevented gliders operating in close proximity to long-term moorings, that could have provided additional validation and calibration of sensors. As part of the programme an instrumented mooring was deployed continuously for 17 months (March 2014 to August 2015). While this mooring location did provide the focal point for many of the specialist glider deployments used in this study, gliders were rarely permitted within 5km of the mooring and so cross-calibration opportunities were limited and the potential for combining data to form an improved combined dataset was compromised.

All gliders used in this study were deployed with factory calibrated sensors. Following deployment every effort was made to collect CTD profiles and discrete water samples for laboratory analysis using the RRS Discovery in close proximity. Within the previously mentioned safety constraints however, the typical separation distance for calibration samples was within 2km, with a number of expected calibration samples and profiles being deemed too far from the glider to be suitable for direct comparison. Prior to recovery of gliders, ship-based measurements were again made in close proximity to gliders with similar distances between the glider and ship. In this case study, only CTDs data within 2km and 3 hours of the glider position was deemed suitable for calibration of oxygen. To compensate for short term variability from internal wave activity, oxygen measurements were compared on density space (as opposed to using depth) with the nearest glider profiles. Even within these strict criteria however, short term variability in surface values of all ocean parameters were often decorrelated between platforms due to patchiness in phytoplankton biomass and upper ocean (meteorologically influenced) hydrography and so data was not used above 10m depth.

Glider deployments related to the CCS to CS2 transect were designed around a single glider operation and so no opportunities were available for cross calibration between glider platforms except when recovery and deployment was being undertaken during the same operation. These were important opportunities for this case study to test the long-term capability of sensors used on the gliders, particularly those that are susceptible to biofouling or sensor drift. Figure 3 shows the combined data from multiple deployments on the CCS to CS2 transect.

In addition to cross-calibration recognised quality control procedures were applied to sensors that were susceptible to sensor lag related problems. These were conductivity (for derivation of salinity) and oxygen.

1. Correction of conductivity data derivation of salinity and density: Errors in salinity and density may occur due to inconsistencies between temperature and conductivity sensors, which are partly attributable to the physical separation of sensors and a disparity in response times, both of which can be simply corrected for. More complex however is the correction for thermal inertia of the conductivity cell (Lueck and Picklo, 1990) as it passes through layers of different temperature. Thermal inertia corrections were made following the methods of Garau et al (2011), who employs optimisation techniques to minimise the disparity between upward and downward glider profiles and which was effective in this study.
2. Correction to oxygen data to account for time lag associated with water passing through the sensor membrane: This lag results in similar problems as thermal inertia in salinity calculations with the largest errors observed at the temperature and oxygen gradient (or oxycline), which is often to point of interest. Data were corrected using the methods of Bittig et al (2014). A strong oxycline during summer months resulted in limited success of this lag correction, with some remaining disparity between upward and downward profiles remaining. Data within upper and lower mixed regions however was suitably corrected using this technique.

Of the remaining sensors; only temperature was directly calibrated against ship-based measurements. Chlorophyll and CDOM fluorescence and OBS were left uncalibrated due to the uncertainties in using the narrowband optical sensor (Wetlabs ECO puck) to measure complex, broad spectrum signals of this type. Chlorophyll-a fluorescence and its relation to phytoplankton biomass is an area of active research and, similar to CDOM and OBS, these data are unlikely to provide a robust estimate of what is a broad spectrum signal that is strongly related to light conditions and phytoplankton community composition (e.g. Kruskopf & Flynn, 2006), and so were used only as qualitative indicators in this study. Additionally, large horizontal gradients in these parameters were observed across the shelf and therefore discrete water samples from CTDs were too far from the glider to use for calibration. Data for these sensors are converted to SI units using factory calibration coefficients.

2.4. Results

2.4.1. <u>Across shelf transect</u>

Data collected for ocean variables temperature, salinity, chlorophyll fluorescence and oxygen concentration are shown in Figure 3. Iridium related communication problems over late December 2014 and into January 2015 resulted in a long period when only a few profiles were collected. Technical failures led to additional shorter periods when no data was collected and quality control criteria were occasionally not met. These periods are indicated by blank sections in Figure 3. The most significant period of data loss due to quality control was the previously identified period of summer bio-fouling.

Following recommencing of data collection in January 2015, the deployed glider (Slocum unit 345 – Cabot) experienced difficulty maintaining steady flight characteristics. Despite continuing to operate up to mid-March the decision was finally made to stop maintaining the CCS to CS2 transect, but instead to hold position close to the CCS mooring for recovery. Prior to this period of data loss, and during all following deployments the gliders display a more ordered flight behaviour. The cause of this poor flight profile was not confirmed however experience suggests something was entangled with the glider, preventing optimal effectiveness of navigation control mechanisms (e.g. plastic debris or lost fixed fishing gear).

The gliders appeared to hold up well against biofouling over the spring bloom period when deployed for a month (unit 397), and for during long periods (unit 345) during winter deployments. The glider deployed across the shelf for a longer period over summer (unit 399), which was sampling through the subsurface chlorophyll maximum, experienced significant biofouling (Figure 4c, Figure 5) on all optical sensors including oxygen. This resulted in significant optode drift and anomalous readings of oxygen which worsened significantly over time from the summer glider. This is clearly evident in Figure 4c where we observed noise in the oxygen with a strong diurnal fluctuation. This signal was more pronounced in the surface (but also visible at depth) and was the result of the 1mm thick algae layer covering the sensor responding to the high light conditions during the day and photosynthesising. This in turn resulted in anomalous electrochemical measurements of DO made by the optode. As this was not a linear drift, and the effect of the biofouling on the oxygen optode worsened rapidly over time, we were unable to correct the data from unit 399 from day 196 and the data was deemed not useable.

Despite gaps in data collection, the glider transect time-series successfully measured multi-parameter conditions during transition from autumn-stratified to winter-mixed to spring and summer stratified conditions. The progression of spring stratification is clearly captured as is the biogeochemical response in phytoplankton abundance (indicated by enhanced chlorophyll fluorescence) and oxygen dynamics. The capability of the gliders to measure within just a few metres of the sea surface has provided new insight into physical controls on winter and spring conditioning from meteorological forcing.

Work currently being investigated from this long-term, high-resolution study include,

- the role of winter and spring conditioning of bottom mixed layer oxygen concentration and the implications for ecosystem health (Dr Charlotte Williams et al, NOC, in prep.).
- physical controls on phytoplankton variability in coastal and shelf seas (University of Liverpool, PhD project).
- Quantifying horizontal exchange mechanisms in the Celtic Sea (University of Liverpool, PhD project).

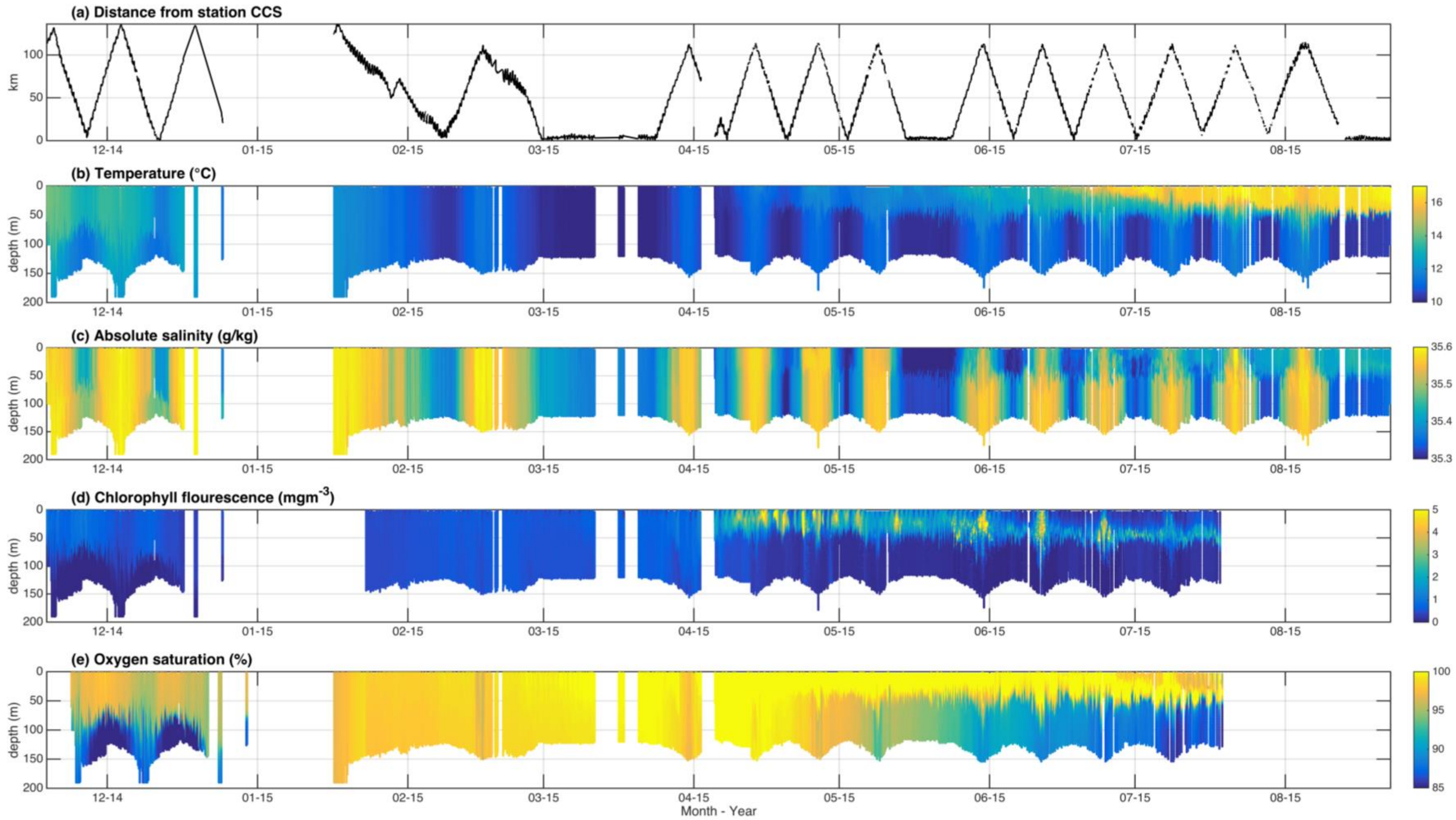

Figure 3: Results from the concatenated time-series of glider transects between stations CCS and CS2 are shown. For reference the distance from station CCS is shown in panel (a). This clearly demonstrates some of the technical difficulties experienced maintaining this long time-series. Following panels show (b) temperature, (c) salinity (d) chlorophyll fluorescence (using factory calibration for unit conversion) and (e) oxygen % saturation.

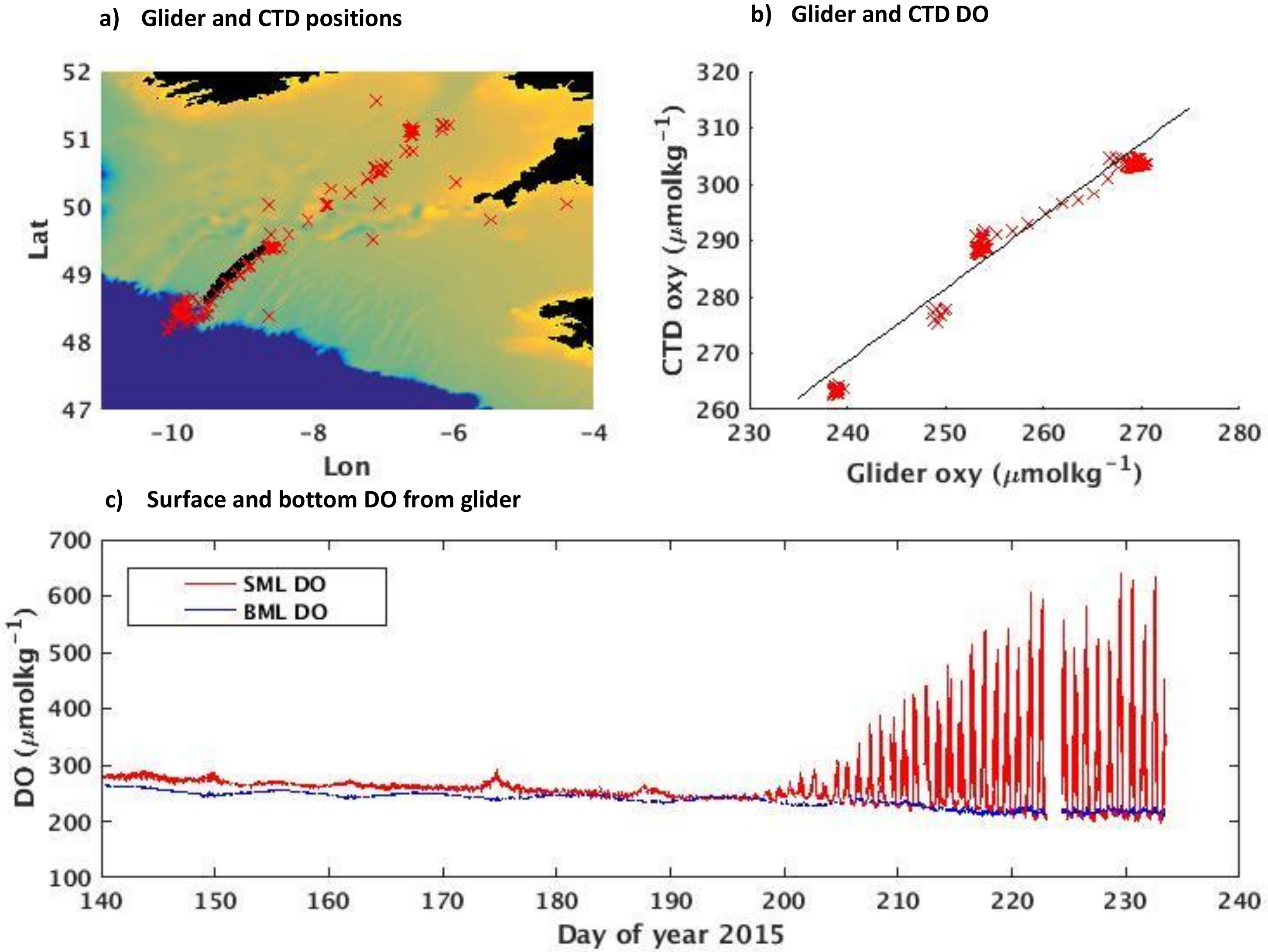

Figure 4: a) The glider track (black line) from CCS to CS2 with SSB CTD positions also shown (red crosses). b) Example calibration of oxygen from unit 397 using oxygen measurements from CTDs at deployment and recovery of glider. c) surface and bottom oxygen concentrations from the summer glider (unit 399), note from day 196 the effect of biofouling to measurements which significantly worsens over time,

Figure 5: Photos of sensors on the summer deployed glider (unit 399) following recovery. The extent of biofouling on exterior components is clearly evident and resulted in critical degradation of data quality from optical sensors.

2.4.2. Specialist glider deployments

In addition to the repeat glider transect (3.4.1) this case study includes multiple deployments of specially equipped gliders; the Ocean Microstructure Glider (OMG) and the Nutrient Sensor Enabled Glider.

2.4.2.1. Ocean Microstructure glider (OMG) deployments

In total, 2 available OMGs (OMG2 and OMG3) were deployed 5 times in two locations (see appendix A for the deployment schedule) with varying levels of success. The first deployment of OMG3 was not successful as a configuration error resulted in no microstructure data being collected.

The 2nd and 3rd deployments took place in April 2015 at the onset of seasonal stratification. These deployments were successful and a total of 21 and 8 days of data were collected close to stations CCS and CS2 respectively at approximately 15 minute resolution producing approximately 1800 and 650 individual profiles of turbulent microstructure data. The high energy associated with the shelf break region at CS2 did have an impact on data quality. This was caused by intense internal wave activity producing vertical velocities that were strong enough to displace the glider during flight, making processing of data difficult. Work is still ongoing with these data. April data collected at CCS was however recoverable and is currently being used in physical and biogeochemical investigations associated with spring stratification and the spring bloom.

The 4th and 5th OMG deployments were a repeat of the spring experiment, including both CCS and CS2 with 21 days (1240 profiles) and 7 days (210 profiles) of data collected respectively. Data from CS2 for this period however were deemed unsuitable for derivation of turbulent parameters due to errors in ballasting of the glider, which led to poor flight characteristics of the glider and excessive noise in the microstructure data. CCS data collection was however successful and provided a high resolution time-series documenting the response of shelf sea stratification under variable tidal, meteorological and internal forcing.

OMG data includes the dissipation of turbulent kinetic energy (ε), which represents that amount of turbulent energy available to mixing and is used to quantify fluxes of heat, momentum, nutrients, oxygen and other water properties, thus forming a critical component of oceanographic and associated environmental studies.

The spring study (left panels Figure 6) provides fine-scale resolution of the physical controls on the onset of seasonal stratification at this typical shelf sea site. The OMG enables quantification of physical forcing from tides, winds, waves and second-order internal processes such as topographically driven internal waves and wind trigger inertial and how the balance of such forces changes with increasing seasonal solar heating.

The summer study (right panels, Figure 6) show how ongoing physical forcing of the system impacts on summer stratified conditions. Both summer and spring OMG time series currently form a key component of ongoing multi-disciplinary research and PhD projects and numerous publications are expected over the coming months.

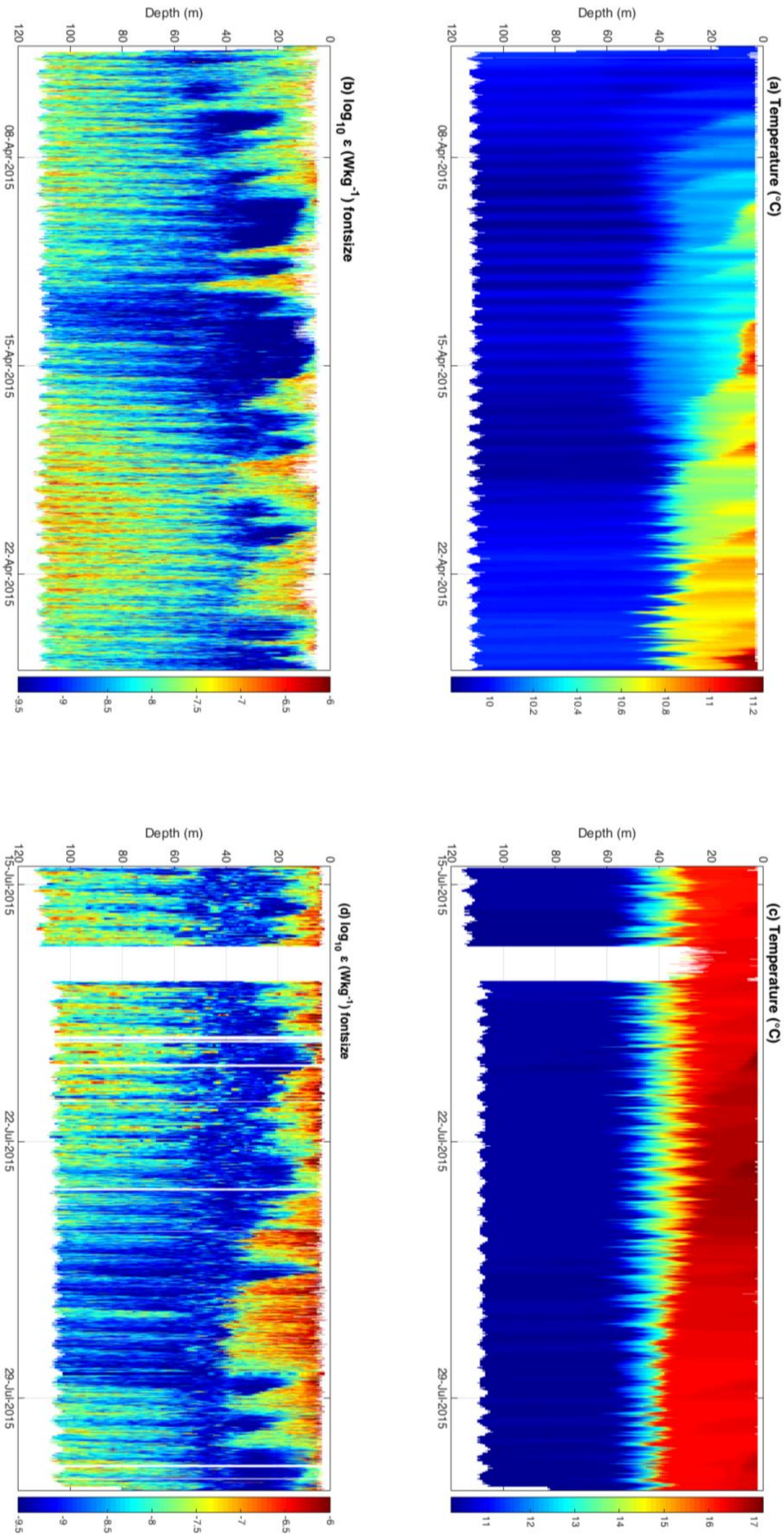

Figure 6: OMG data from (left) spring and (right) summer periods 2015. Upper panels show temperature and lower panels show coincident measurements of the dissipation rate of turbulent kinetic energy (log10 scale).

2.4.2.2. Nutrient Sensor Enabled Glider (NSEG)

The NOC has developed world leading capability in the design and manufacture of so-called 'Lab-on-a-chip' microfluidic nutrient sensors that are small enough and sufficiently self-contained to permit integration into variants of ocean gliders, termed Nutrient Sensor Enabled Gliders, or NSEGs. The UK SSB programme formed part of the development roadmap (see AtlantOS D6.1) and validation process (AtlantOS D6.3) of these novel sensors as part of its glider survey. Technical details of these sensors and results can be found in recent publications (e.g. Beaton et al, 2012; Nightingale et al, 2015; Beaton et al, 2017).

All NSEGs in this case study used Seaglider Denebola (SN534) with an integrated nutrient sensor configured to measure in situ nitrate concentration. Deployments were designed to coincide with OMG deployments at CCS to enable combining of data to calculate vertical nutrient fluxes and their contribution to seasonal shelf sea biogeochemical dynamics and to take advantage of nearby calibration samples collected from RRS Discovery. Unfortunately, sensor failure on the first deployment (Appendix A, Q4 2014) resulted in no nutrient data being collected. The first successful mission was April 2015 (Q2 2015). The NSEG achieved 776 individual profiles, 145 of which successfully recovered nitrate concentration data. Nitrate data collected for this deployment is presented in Figure 7.

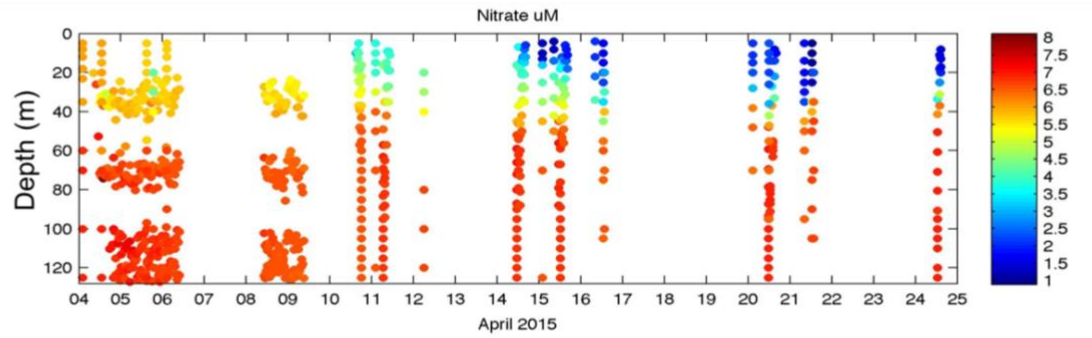

Figure 7: Nitrate concentration data collected using the NSEG during spring 2015. Each point indicates a discrete sample analysed by the lab-on-a-chip. The different sampling regimes of the nutrient sensor are clearly evident, with continuous sampling before and using the loiter-dive method after April 10th (Data courtesy of Alex Vincent, University of Southampton)

NSEG data including nitrate were calibrated against nearby discrete water samples collected by the RRS Discovery CTD rosette. Coincident measurements made by the NSEG identified a robust linear relationship between density and nitrate concentration, which was used to extend the coverage of nutrient data at the higher temporal and spatial resolution provided by the NSEG CTD (Figure 8).

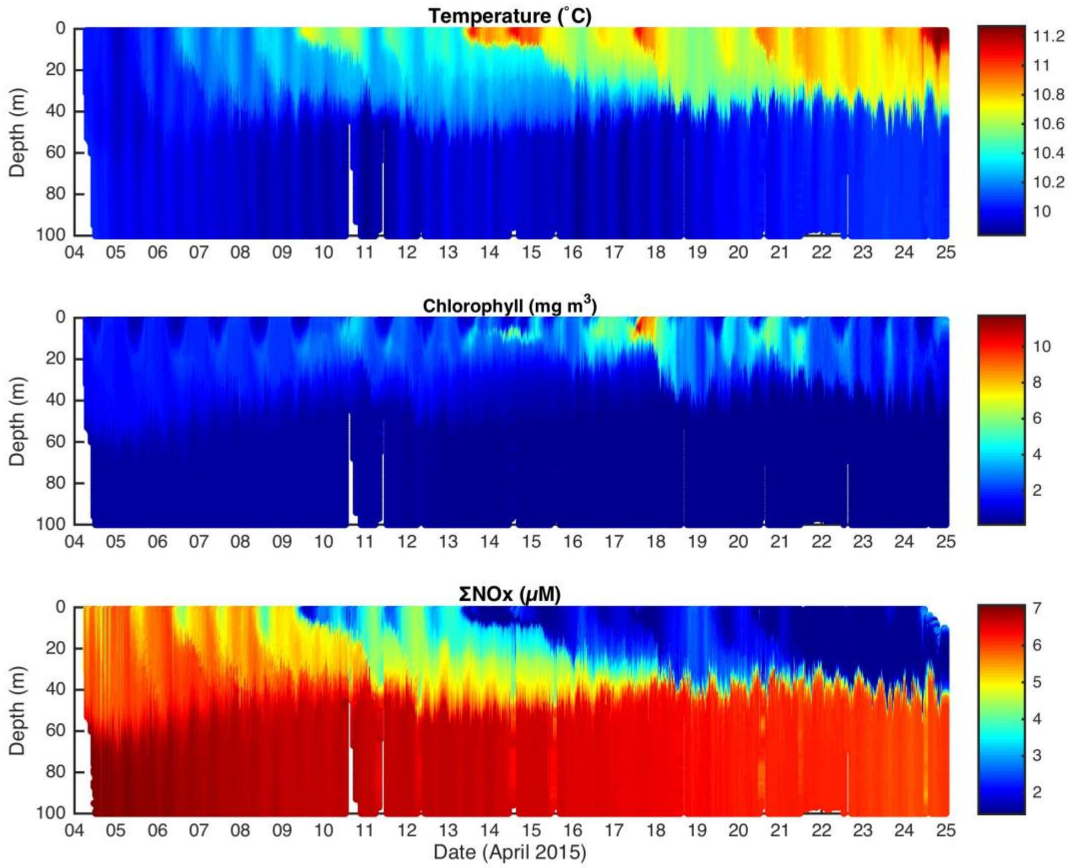

Figure 8: Coincident temperature (upper), cholorphyll a (middle) and nitrate (lower panel) data collected by the NSEG during April 2015 reveal the drawdown of surface nutrients during the onset of seasonal stratification and subsequent spring bloom period (Data courtesy of Alex Vincent, University of Southampton)

As with the OMG and transect data collected in this case study, the NSEG captured the transitional state of multiple ocean parameters during the onset of seasonal stratification in high temporal resolution. Nutrient drawdown in the upper layer is identified to be gradual during the early stages of stratification, prior to the increase in surface chlorophyll associated with the spring phytoplankton bloom occurring 16th to 22nd April. At this point nitrate is rapidly depleted to result in a strong nitrate gradient (or nitracline) separating near zero surface concentrations from replete bottom mixed layer values around 6μM.

The planned summer deployment of the NSEG was also successful. The NSEG achieved 776 individual profiles, 145 of which successfully recovered nitrate concentration data. Following lessons learned during the spring deployment, nutrient sampling was managed more regularly, which improved temporal coverage of nitrate data throughout the 3 week deployment (Figure 9).

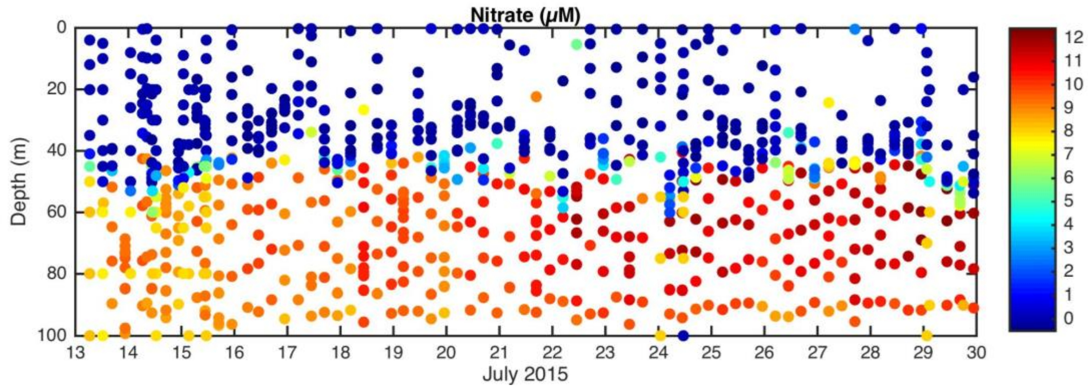

Figure 9: *Nitrate concentration (bottom) data collected using the NSEG during summer 2015. Each point indicates a discrete sample analysed by the lab-on-a-chip. More consistent sampling methods produced imporved temporal and (vertical) spatial coverage of data than the previous spring deployment (Data courtesy of Alex Vincent, University of Southampton).*

2.5. Data delivery

Because data were collected under funding from the UK Natural Environment Research Council (NERC), data were managed following the NERC established Data Policy. This Data Policy commits that NERC-funded scientists must make their data openly available within two years of collection and deposit it in a NERC data centre for long term preservation, with the aim that all NERC-funded data are managed and made available for the long-term for anybody to use without any restrictions. The glider data presented in this case study are all currently available in their final quality controlled form under request to the British Oceanographic Data Centre (BODC), contactable by email (enquiries@bodc.ac.uk) or via its online data portal (https://www.bodc.ac.uk/). Near future plans are for all data collected during this case study to be made publicly available in the internationally recognized EGO NetCDF format, stemming from the EGO glider network supported under AtlantOS WP3 task 3.4 (www.ego-network.org).

3. Summary

This study has provided a valuable dataset that enables investigation of the physical and biogeochemical functioning of a typical temperate latitude shelf sea system. The deployment strategy has enabled both broad scale variability to be captured over seasonal time scales, with 27 repeat transects over 100km in length between the shelf break, where the continental shelf sea meets the deep ocean, and the inner shelf. This repeat transect captures coincident measurements of physical (temperature, salinity and density) and biogeochemical (chlorophyll, CDOM, OBS and oxygen) parameters at extremely high resolution over a 9-month period covering late-autumn, winter, spring and summer conditions. Vertical measurements made at 1Hz provide vertical resolution of approximately 15-20cm and piloting strategies enable repeat up-down profile pairs at sub-kilometre scales. This time-series therefore permits resolution of a broad spectrum of ocean processes, from the mesoscale (order 10-100km) to sub-mesoscale (order 100s of metres).

Numerous technical failures did interrupt the repeat transect, the largest of which being interrupted satellite communications and subsequent technical difficulties during December-January 2014 (Figure 3), but shorter-lived problems also caused gaps in data collection ranging from hours or a few days, to a week. Despite this, the seasonal variability of the system was successfully captured, which permits research into physical to biogeochemical functioning on seasonal, annual and interannual timescales.

Deployments with the specialist gliders OMG and NSEG have provided complementary data to the glider transect time-series. These data provide quantifiable understanding of the mixing mechanisms that control physical and biogeochemical dynamics in this shelf sea system by providing direct measurements of turbulent mixing (OMG) and the cycling of limiting nutrients (NSEG). These key components of the shelf sea physical budget and nutrient inventory will permit extrapolation of understanding developed at the CCS station to the broader context of the across shelf transect.

The low-power buoyancy propulsion of ocean gliders restricts their speed of movement in such a dynamic environment. The influence of tides on the progress of these autonomous systems is clearly identifiable in glider track data (Figure 1) and made attempts to hold a quasi-stationary position difficult. Whether the collective contribution from all gliders deployed in this study contribute to a truly synoptic view of shelf sea functioning is still open to debate. Clearly, using a single, slow-moving glider to cover large areas leads to a loss of information over regions that are infrequently sampled. The transit time for a return transect from CCS-CS2-CCS was typically around 13 days duration. The region under investigation is strongly influenced by spring-neap variability (occurring due to the interaction between lunar and solar tides and shallow water tidal amplification), which has a period of around 14 days. There is therefore a likelihood of under-sampling that will likely lead to aliasing of the spring-neap variability. The strongest mechanism controlling variability in this system however is the seasonal cycle of stratification by solar heating. Spring measurements made with the OMG (Figure 6) and NSEG (Figures 7 & 8) clearly demonstrate the dramatic transition that occurs during onset of these conditions, from well mixed winter conditions to spring stratification. The collective dataset presented in this case study can therefore be consider a synoptic, multi-variable study on seasonal time scales.

These deployments marked a transitional point for European ocean glider operations as this was its first coordinated attempt to manage extended period deployments of multiple gliders with different configurations and objectives towards a common goal. Lessons learnt during this operation have provided the skills and knowledge base to undertake subsequent ambitious project involving multiple autonomous marine vehicles. The final comments and recommendations below were drawn with the support of the AtlantOS programme.

4. Final comments and recommendations

a) Gliders offer long-term, relatively inexpensive options for collection of essential ocean variables (EOVs). The contribution that glider technology is making within the marine sector is growing and is now extending beyond the ocean research environment; providing options for statutory marine monitoring, defence sectors and energy sectors. As with any long-term deployment of instrumentation however, validation and calibration of sensors to provide trustworthy data for these sectors is critical. Glider users must take responsibility for the quality assurance and control of data being collected to ensure the development of trust for such platforms within the global ocean community.

Recommendation: Glider users should keep an open dialogue with platform and sensor manufacturers to ensure optimal configuration of platforms based on user requirements. Recognised data quality standards should be adopted to ensure good data quality and unified data formatting for global transferability.

b) A weakness of this experiment was a lack of redundancy, which led to periods of data loss. This came under 2 categories, the lack of duplication of sensors and platforms (i.e. gliders)
   - The standard configurations of gliders (Slocum and Seaglider) provide no duplication of sensors, and so single sensor failure results in an immediate loss of data. This also reduces the opportunity to check for sensor drift, restricting cross-calibration or data checking to periods where gliders are near other sensor platforms.
   - The deployment of single gliders for the CCS-CS2 transect was designed to be cost effective, enabling maximum duration of the work under limited resources. Technical failure of a single glider therefore resulted in an immediate gap in data collection. During winter conditions, when ship visits to the area were only every 3 months, this resulted in the longest data gap.

Recommendation: data loss in this case study primarily came from platform failure rather than sensor malfunction. To maximise future data collection capability therefore it is recommended to provide secondary gliders in close proximity to primary units. The second biggest loss of data was from bio-fouling during summer months. Duplication of sensors on single gliders is unlikely to resolve this issue so efforts should be made to employ best practice techniques to prevent biofouling following advice provided under AtlantOS WP6 task 6.4. Sensor duplication would be beneficial to check for sensor drift, however provision of a secondary glider in close proximity would enable regular cross-calibration and opportunities to identify sensor drift so is the recommended best practice.

c) Despite their potential for making sustained measurements economically, gliders are slow moving marine vehicles, dependent on buoyancy control to navigate through potentially dynamic environments. This makes navigation difficult and complicates data analysis and opportunities for calibration. Recent technological developments have included propeller options to Slocum gliders, that dramatically increase maximum capable glide speeds up to approximately $1 ms^{-1}$ for improved navigation capability. The majority of glider navigation however is still managed by human pilots and this study took no advantage of the large range of ocean modelling capability to predict conditions to optimise navigation between waypoints or to hold position close to the CCS mooring. Current developments are moving towards intelligent, fully autonomous navigation and adoption or trials of such methods are encouraged for future glider experiments.

Recommendation: Glider pilots and managers should aim to incorporate all available technologies and predictive capability to optimise navigation, particularly in highly dynamic environments such as continental shelf seas.

Each of these recommendations have now been incorporated into subsequent multiple glider missions undertaken by the UK MARS facility and are now being advised as best practice to partner programmes. Recent examples that have benefited from our analysis and recommendations include the following projects;

I. **MASSMO4** was the latest in a series of demonstrator missions sponsored by the UK Defence Science and Technology Laboratory in support of the UK Royal Navy and included UK academic institutes and in partnership with NATO Centre for Maritime Research and Experimentation, Marine Science Scotland and industry partners. This multiple deployment of ocean gliders was aimed at providing synoptic realisation of mesoscale ocean features on the West Scotland shelf and northeast Atlantic in the summer of 2017 (http://projects.noc.ac.uk/massmo/).

a) This study successfully deployed gliders in small groups of 2-3 to meet cross-calibration and redundancy objectives.

b) MASSMO4 also successfully incorporated regional scale ocean model data to assist pilots and optimise planning.

c) Lastly, MASSMO4 incorporated new passive acoustic technologies in collaboration with manufacturers and industry partners. This acoustic study will contribute to future AtlantOS deliverable D4.6.

II. **AlterEco** is an ongoing, long-term study that has maintained continuous occupation of an ecologically important region of the North Sea since November 2017, with an expected end date of February 2019. This experiment represents a next-step development from the study presented in this report, as it aims to test the capability of ocean gliders to undertake marine monitoring that might be considered suitable to meet strategic monitoring responsibilities (e.g. EU Marine Strategy Framework Directive, Oslo-Paris Convention for the Protection of the Marine Environment of the North-East Atlantic). AlterEco benefits directly from the skills developed during AtlantOS funding by retaining that researcher and is led by the same PI. This study was developed following the recommendations presented in this report;

a) AlterEco uses a minimum of 2 gliders on each 3-month deployment to provide redundancy and continuous cross-calibration potential. During periods of more intense activity, when up to 5 gliders are in operation, central waypoints are used to ensure regular crossing of glider pathways to additional calibration opportunities.

b) AlterEco pilots use model forecasts to assist in the piloting of gliders. These forecasts are currently provided as a guide on the online portal, however future developments will include real-time delivery of model forecasts to gliders to assist in fully automated piloting (planned November 2018).

c) The biogeochemical requirements of AlterEco require regular provision of state-of-the-art nutrient sensors to enable seasonal coverage of macro-nutrient cycles. Developments under AtlantOS WP6, task 6.1 (Sensors and new instrumentation) are providing new capability in this field and are directly funding engineer support of nutrient sensor integration into a range of ocean gliders for use in AlterEco, which forms part of the roadmap for ocean sensor development (AtlantOS D6.1). AlterEco will subsequently trial the first glider deployment of a phosphate micro-fluidic nutrient sensor (developed at the UK NOC) as part of AtlantOS D6.3.

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Appendix A:

The following table provides details of gliders deployed in each operational quarter of the SSB programme. Shading indicates time-series collected at specific locations or related to specific repeat transects. Please refer to the map in Figure 1.

				2014			2015		
Glider name	**Glider type and S/N**	**Sensors**	**Mission**	**Q2**	**Q3**	**Q4**	**Q1**	**Q2**	**Q3**
STELLA	Slocum/436	CTD Chl, CDOM, BBP Oxygen	CS2 (butterfly transect)						
RALEIGH	Slocum/399	CTD Chl, CDOM, BBP Oxygen PAR	CS2 (butterfly transect)						
BELLAMITE	Slocum/330	CTD Chl, CDOM, BBP Oxygen	CS2 - Offshelf transect						
AMMONITE	Slocum	CTD Chl, CDOM, BBP Oxygen	CS2 - Offshelf transect						
BOONDOGGLE	Slocum/437	CTD Chl, CDOM, BBP PAR Oxygen	CS2 - Offshelf transect					Lost at Sea	
CANOPUS	Seaglider/533	CTD Chl, CDOM Oxygen	CS2 - Offshelf transect						
GROWLER	Slocum/408	CTD Chl, CDOM, BBP Oxygen	CS2 - Offshelf transect						
CABOT	Slocum/345	CTD Chl, CDOM, BBP Oxygen	CCS - CS2 transect						
FORTYNINER	Slocum/419	CTD Chl, CDOM, BBP Oxygen	CCS - CS2 transect						
NELSON	Slocum/397	CTD Chl, CDOM, BBP Oxygen	CCS - CS2 transect						
RALEIGH	Slocum/399	CTD Chl, CDOM, BBP PAR Oxygen	CCS - CS2 transect						
OMG 3	Slocum/424	CTD Oxygen Turbulence	CCS MOORING						
DENEBOLA	Seaglider/534	CTD chl, CDOM, BBP Nitrate sensor Oxygen	CCS MOORING						
OMG 3	Slocum/424	CTD Oxygen Turbulence	CCS MOORING						
DENEBOLA	Seaglider/534	CTD chl, CDOM, BBP Nitrate sensor Oxygen	CCS MOORING						
OMG2	Slocum/423	CTD Oxygen Turbulence	CCS MOORING						
DENEBOLA	Seaglider/534	CTD chl, CDOM, BBP Nitrate Oxygen	CCS MOORING						
OMG 2	Slocum/423	CTD Oxygen Turbulence	CS2 MOORING						
OMG3	Slocum/424	CTD Oxygen Turbulence	CS2 MOORING						
CANOPUS	Seaglider/533	CTD Chl, CDOM Oxygen	CS2 MOORING						
DRAKE	Slocum/400	CTD Chl, CDOM, BBP Oxygen	CCS - Onshore transect						
ZEPHYR	Slocum/306	CTD Chl, CDOM, BBP Oxygen	CCS - Onshore transect						